- Why double beta decay?
- The physics
- General issues
- Some experiments (GERDA, COBRA)
- New results
- Alternative modes
- Questions/info
- Summary
intrinsic particle-antiparticle symmetry of neutrinos?

**Dirac neutrino**

- 4 \( \nu \) states
- lepton number conservation \( \Delta L = 0 \)
- neutrino \( \neq \) antineutrino

**Majorana neutrino**

- 2 \( \nu \) states
- lepton number violation \( \Delta L = 2 \)

\( \nu^D \) and \( \nu^M \) only distinguishable if \( m_\nu \neq 0 \)
Double beta decay

- \((A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e\) \(2\nu\beta\beta\)
- \((A,Z) \rightarrow (A,Z+2) + 2e^-\) \(0\nu\beta\beta\)

Unique process to measure character of neutrino

The smaller the neutrino mass the longer the half-life

Neutrino mass measurement via half-life measurement

Requires half-life measurements well beyond \(10^{20}\) yrs!!!!

Only 35 isotopes in nature are able to do that!
There are only 35 candidates  K. Zuber
Any $L=2$ process can contribute to $0\nu\beta\beta$

$\frac{1}{T_{1/2}} = PS \cdot NME^2 \cdot \varepsilon^2$

Nice interplay with LHC
Light Majorana neutrinos

\[ \mathcal{E} \equiv \langle m_\nu \rangle = \sum_i U_{ei}^2 m_{\nu_i} \]

\[ \frac{1}{T_{1/2}} = PS \times NME^2 \times \left( \frac{\langle m_\nu \rangle}{m_e} \right)^2 \]

Schechter and Valle 1982:
Independent of mechanism for neutrinoless DBD
Majorana neutrino mass will appear in higher order!

Observe $0\nu\beta\beta$ aecay

\[ \equiv \]

Neutrinos are Majorana particles

K. Zuber
Schechter Valle theorem

General:

Schechter - Valle:

\[ \delta m_\nu = \frac{128 g^4 G_F^2 \epsilon_3 m_u^2 m_e^2 m_d^2}{(16\pi^2)^4 m_p} \times \left[ C_0^2 (M_W^2/\mu^2) + 2C_{-1}(M_W^2/\mu^2)C_1(M_W^2/\mu^2) + 2C_{-2}(M_W^2/\mu^2)C_2(M_W^2/\mu^2) \right] = 9.4 \times 10^{-25} \text{ eV} \]


Other neutrino mass operator necessary

K. Zuber
Neutrino oscillations

\[ |\nu_i\rangle = \sum U_{\alpha i} |\nu_\alpha\rangle \]

Oscillation probability:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\Theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E} \right) \]

with

\[ \Delta m^2 = m_2^2 - m_1^2 \]

2 flavour scenario

3 flavour scenario

PMNS - Mixing matrix (like CKM matrix for quarks)

K. Zuber
Neutrinos mix as oscillation experiments have shown, hence

Leptonic mixing (PMNS) matrix (including Majorana character)

\[
U = \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i \delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{i \delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i \alpha_1} & 0 \\
0 & 0 & e^{i \alpha_2}
\end{pmatrix}
\]

From oscillation experiments:

- \(\sin^2 2\theta_{23} > 0.9\) (90% CL), best fit \(\theta_{23} = 45^\circ\)
- \(\sin^2 2\theta_{13} = 0.09\) (90% CL), \(\theta_{13} = 9^\circ\)
- \(\sin^2 \theta_{12} = 0.32, \theta_{12} = 34.06^\circ_{+1.16}^{-0.84}\) K. Zuber

\[
\langle m_\nu \rangle = \sum_i U_{ei}^2 m_{\nu_i} = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i \alpha_1} m_2 + s_{13}^2 e^{i \alpha_2} m_3
\]
Mass hierarchies and DBD

1.) Is the claimed evidence correct? GERDA phase I

2.) Can we probe the inverted hierarchy?

3.) What about the normal hierarchy?
Mass hierarchies and DBD

With the known oscillation results everything is fixed

General dependence

Current data

Other mass determinations

**Beta decay:**

\[ m_\beta = \left( c_{13}^2 c_{12} m_1^2 + c_{13}^2 s_{12} m_2^2 + s_{13}^2 m_3^2 \right)^{\frac{1}{2}} \]

**Cosmology:**

\[ \Omega_\nu h^2 \implies \sum = m_1 + m_2 + m_3 \]

\[ \sum m_\nu < 0.23 \text{eV} \ (95\% \text{C.L.}) \]

KATRIN – Sensitivity about 0.2 eV

+ oscillation parameters
The search for $0\nu\beta\beta$

or

K. Zuber
This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

\[ T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta} \ (\tau_{\beta\beta}) \ (\text{Background free}) \]

For half-life measurements of $10^{26-27}$ yrs

1 event/yr you need $10^{26-27}$ source atoms

This is about 1000 moles of isotope, implying about 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...
Going underground
0νββ: Peak at Q-value of nuclear transition

Measured quantity: Half-life

\[
\frac{1}{T_{1/2}} = PS \times NME^2 \times \left(\frac{<m_\nu>}{m_e}\right)^2
\]

Experimental sensitivity depends on

\[
T_{1/2}^{-1} \propto a \varepsilon \sqrt{\frac{M \cdot t}{\Delta E_B}} \quad \text{(BG limited)}
\]

\[
T_{1/2}^{-1} \propto a \varepsilon M \cdot t \quad \text{(BG free)}
\]

If background limited

\[
m_\nu \propto \sqrt[4]{\frac{\Delta E_B}{M \cdot t}}
\]

K. Zuber
Master equation

\[ \frac{1}{T_{1/2}} = PS \times NME^2 \times \left( \frac{\langle m_\nu \rangle}{m_e} \right)^2 \]

Measurement

Exact calculation

Complex calculations

Quantity of interest

J. Kotila, F. Iachello, PRC 034316 (2012)
S. Stoica, M. Mirea, arXiv:1307.0290

Several talks at this workshop

K. Zuber
NME – Intermediate states

$$2\nu\beta\beta$$

Virtual

transition

$$0\nu\beta\beta$$

Virtual

transition

K. Zuber
Several new techniques applied in last years

Rescaled as people use different $g_A$ (1-1.25) and $R_0$ (1.0-1.3 fm)

$4 \pm \sqrt{4}$ would do it
Within the Standard Model lepton number is conserved, and so neutrinoless double beta decay (ONUBD) is forbidden. However, recent neutrino oscillation experiments have shown that neutrinos are massive particles, and imply that the description of neutrinos within the Standard Model is incomplete. To move beyond the Standard Model and formulate a new theoretical framework with which to describe neutrino phenomenology, the mass mechanism must be investigated. UNBBD experiments illuminate the nature of the mass term in the neutrino Lagrangian. If ONUBD is observed, the neutrino must be a Majorana particle. This represents both theoretical and experimental challenge. In particular, the extraction of precise information on neutrinos is impossible without a detailed understanding of the nuclear matrix elements that enter in the expressions for the decay widths.

The Workshop will focus on the status of and prospects for the nuclear matrix element calculations and measurements that are a key factor in extracting information on the neutrino masses in neutrinoless double beta decay processes.

The Workshop will take place at the Institute for Particle Physics Phenomenology, University of Durham, Durham, UK. Participants will be accommodated nearby. Because accommodation is strictly limited, attendance is on invitation only. If you wish to attend, please email one of the organizers listed below.

The meeting will start at 9.00am on Monday 23rd May and end at lunchtime on Tuesday 24th May 2005. Participants are expected to arrive on Sunday 22nd May. There is no fee and participants' local costs will be paid by the IPPP. There will a conference dinner on the evening of Monday 23rd May, and buffet lunches will be provided on both days.

Programme
Participants
Travelling to Durham

Organisers:
Kai Zuber (Sussex), James Stirling (Durham), Linda Wilkinson (Durham)
Items studied

D. Frekers, H. Ejiri et al., RCNP Osaka

D. Zinatulina, MEDEX 2013

TITAN-EC at TRIUMF

Difference in neutron vacancies

\[
\begin{align*}
\text{76Ge} & \rightarrow \text{76Se} \\
\end{align*}
\]

$0^{\nu}\beta\beta$ decay rate scales with $Q^5 \rightarrow$ only those with $Q > 2000$ keV

11 isotopes of interest

<table>
<thead>
<tr>
<th>Isotope</th>
<th>AME 2003</th>
<th>Q-values 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca-48</td>
<td>4272 ± 4</td>
<td>4262.96 ± 0.84</td>
</tr>
<tr>
<td>Ge-76</td>
<td>2039.006 ± 0.050</td>
<td>2039.006 ± 0.050</td>
</tr>
<tr>
<td>Se-82</td>
<td>2995.5 ± 1.9</td>
<td>2997.9 ± 0.3</td>
</tr>
<tr>
<td>Zr-96</td>
<td>3347.7 ± 2.2</td>
<td>3347.7 ± 2.2</td>
</tr>
<tr>
<td>Mo-100</td>
<td>3035 ± 6</td>
<td>3034.40 ± 0.17</td>
</tr>
<tr>
<td>Pd-110</td>
<td>2004 ± 11</td>
<td>2017.85 ± 0.64</td>
</tr>
<tr>
<td>Cd-116</td>
<td>2809 ± 4</td>
<td>2813.50 ± 0.13</td>
</tr>
<tr>
<td>Sn-124</td>
<td>2287.8±1.5</td>
<td>2292.64 ± 0.39</td>
</tr>
<tr>
<td>Te-130</td>
<td>2530.3 ± 2.0</td>
<td>2527.518 ± 0.013</td>
</tr>
<tr>
<td>Xe-136</td>
<td>2462 ± 7</td>
<td>2457.83 ± 0.37</td>
</tr>
<tr>
<td>Nd-150</td>
<td>3367.7 ± 2.2</td>
<td>3371.38 ± 0.20</td>
</tr>
</tbody>
</table>

Candles
GERDA, Majorana
SuperNEMO, LUCIFER

MOON, AMore

COBRA

CUORE, SNO+
EXO, KamLAND-Zen, NEXT, XMASS

MCT, SuperNEMO(?)
Isotope of interest: 76Ge
• The detectors are decaying!!
• 5 isotopical enriched Ge-detectors
• Sum energy -> Peak at 2039 keV

Still only 1 decay per year per 10 kg Ge

Background obtained 0.1 count/keV/kg/yr
2001

Evidence?

2004

H.V. Klapdor-Kleingrothaus et al.,

2006

90% c.l.

T_{1/2} = 2.23 \pm 0.4 \times 10^{25} \text{ yr}

H.V. Klapdor-Kleingrothaus et al.,

Very controversial discussion in the community

If right, neutrino mass is around 0.3 eV and masses are almost degenerate

K. Zuber
KamLAND - Zen

Using 400 kg of Xe (91.7% enriched in Xe-136)

Upgrade to 1 ton enriched Xe planned in 2014

A Gando et al., PRC 85,045504 (2012)

$$T_{1/2}^{0\nu} > 5.7 \times 10^{24} \text{ yr (90\% C.L.)}$$

A. Gando, arXiv:1211.3863

$$T_{1/2} > 1.9 \times 10^{25} \text{ years (90\%CL)}$$

K. Zuber
200 kg of enriched (80%) Xe-136 at hand

First half-life limit on 0nu decay: 
\[ T_{1/2} > 1.6 \times 10^{25} \text{ years (90\% CL)} \]
M. Auger et al., PRL 109, 032505 (2012)

In conflict with positive claim for almost all matrix element calculations

Uncertainties due to conversion

First observation of 2nu decay of Xe-136, 
N. Ackerman et al., PRL 107, 212501 (2011)

Future option: Barium tagging
Idea: Running bare Ge crystals in LAr

- Ultra pure water (580 m³): n moderator, Cherenkov medium for μ veto
- Steel cryostat with internal copper shield
- High-purity LAr (64 m³): shield and coolant
- Option: active veto

The Gerda experiment for the search of 0νββ decay in 76Ge
GERDA - Installation impressions
Deployed all phase I detectors in Nov. 2011 together with 1 natural HPGe detector
Phase I data taking

- **enriched coaxials, 16.70 kg × yr**
- **enriched BEGes, 1.80 kg × yr**
- **GTF 112, 3.13 kg × yr**

K. Zuber
Phase I data taking

16.7.2013

Bi-214 1765 keV

Bi = 0.024 cts/(keV kg yr)

Bi-214 2204 keV

TI-208 2614 keV

enriched coaxials, 13.65 kg × yr
natural coaxials, 4.69 kg × yr
Phase I data analysis

Blind analysis
(40 keV around peak)

Background model
(flat background in region of 200 keV around signal after removing lines)

BI prediction for peak region: $17.6 \text{ to } 23.8 \times 10^{-3} \text{ cts/(keV kg yr)}$

arXiv:1306.5084
Phase I results

Pulse shape discrimination: M. Agostini et al. arXiv:1307.2510

Result Phase 1: M. Agostini et al., 1307.4720
Signal to background ratio > 4 : 1

Phase I results - 2ν DBD half-life

Measurement of the half-life of the two-neutrino double beta decay of $^{76}$Ge with the GERDA experiment

$$T_{1/2}^{2\nu} = (1.84^{+0.14}_{-0.10}) \times 10^{21} \text{yr}$$

Averaging is tricky!
2. $^{76}\text{Ge}$

1. $(0.9 \pm 0.1) \times 10^{21}$ yr  
   \( (S/B \approx 1/8, \ N \approx 4000) \)

2. $1.1^{+0.6}_{-0.3} \times 10^{21}$ yr  
   \( (S/B \approx 1/6, \ N = 758) \)

3. $1.2^{+0.2}_{-0.1} \times 10^{21}$ yr  
   \( (0.93^{+0.2}_{-0.1} \times 10^{21} \text{ yr}) \)  
   \( (S/B \approx 4, \ N = 138) \)

4. $(1.45 \pm 0.15) \times 10^{21}$ yr  
   \( (S/B \approx 1.5, \ N \approx 3000) \)

5. $[1.74 \pm 0.01 \text{(stat)}^{+0.18}_{-0.16} \text{(syst)}] \times 10^{21}$ yr  
   \( (S/B \approx 1.5, \ N = 64000) \)

6. $[1.84^{+0.39}_{-0.08} \text{(fit)}^{+0.11}_{-0.06} \text{(syst)}] \times 10^{21}$ yr  
   \( (S/B \approx 4, \ N \approx 7030) \)

\[ 1.42 \pm 0.03 \pm 0.13 \times 10^{21} \]
\( S/B = 1.3/1 \quad N = 5665 \)

Average value: \( 1.60^{+0.13}_{-0.1} \times 10^{21} \text{ yr} \)

\[ [ \ 2009: (1.5 \pm 0.1) \times 10^{21} \text{ yr } ] \]
1994 two papers on 2nu DBD in 76Ge

Used (why???)

F. Avignone, PNPP 32, 223 (1994)

Not used (why ???)

A. Balysh et al, PLB 322, 176 (1994)

Heidelberg -- Moscow

K. Zuber
Use large amount of CdZnTe Semiconductor Detectors

Focus on $^{116}$Cd

48 detectors running at LNGS, 64 by end of the year

Advantages

- Source = detector
- Semiconductor (Good energy resolution, clean)
- Room temperature
- Modular design (Coincidences)
- Industrial development of CdTe detectors
- $^{116}\text{Cd}$ above 2.614 MeV
- Tracking („Solid state TPC“)
According to simulations particle identification due to pixels should reduce background by 3 orders of magnitude

Semiconductor tracker, Solid state TPC (unique)
4-fold non-unique beta decay \((1/2^+ \rightarrow 9/2^+)\)

**Rate Spectrum**

\[
\begin{align*}
T_{1/2} &= 8.00 \pm 0.11\,(\text{stat.}) \pm 0.24\,(\text{sys.}) \times 10^{15}\,\text{years} \\
\text{48 independent measurements of the half-life!}
\end{align*}
\]

**Q-value:**

\[
322 \pm 0.3\,(\text{stat.}) \pm 0.9\,(\text{sys.})\,\text{keV}
\]


Fits extremely well to AME 2012

**Microscopic calculation:**


4-fold forbidden beta decays – $^{50}$V

Two more: $^{115}$In (well measured), $^{50}$V

$^{50}$V

\[ \begin{align*}
2^+ & \rightarrow 6^+ \quad \text{EC} \\
& \quad Q = 2205 \text{ keV} \\
& \quad \beta^- > 10^{18} \text{ a} \\
6^+ & \rightarrow 2^+ \quad Q = 1038 \text{ keV} \\
2^+ & \rightarrow 0^+ \quad 783.3 \text{ keV} \\
0^+ & \rightarrow 50^{\text{Cr}} \quad 1553.8 \text{ keV} \\
0^+ & \rightarrow 50^{\text{Ti}}
\end{align*} \]

H. Dombrowski, S. Neumaier, K. Zuber, PRC 83, 054322 (2011)

Only limit on beta branch

Higher forbidden beta decays (48Ca, 96Zr) --> DBD is more likely!
Inverse hierarchy:

\[
\langle m_\nu \rangle = \sum_j U_{ej}^2 m_j
\]

\[
\approx c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2
\]

\[
\approx (c_\odot^2 - s_\odot^2) \sqrt{\Delta m_{Atm}^2}
\]

\[
\approx 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}} \text{ eV} \approx 19 \text{ meV}
\]

Just to touch the IH

$^{100}$Mo and $^{150}$Nd seems most promising

Dependence on solar mixing angle

$m_3 = 0.001 \text{ eV}$

Reminder: Factor 2 in mass implies factor 16 in experimental parameters ➔ better solar measurement ➔ SNO+?? Reactors (JUNO, RENO-50)???
Tackling the normal hierarchy

- Will be tough and expensive
  - > tonne scale detectors
- Needs more precise data from oscillations

- New background components (f.e. solar neutrino-electron elastic scattering)


- More accurate matrix elements

  HOW???

Experiments which work for IH and claim might not work for NH
Alternative modes

- \((A,Z) \rightarrow (A,Z-2) + 2 \, e^+ \, (+2 \nu_e)\) \quad \beta+\beta+
- \(e^- + (A,Z) \rightarrow (A,Z-2) + e^+ \, (+2 \nu_e)\) \quad \beta+/EC
- \(2 \, e^- + (A,Z) \rightarrow (A,Z-2) \, (+2 \nu_e)\) \quad EC/EC

\[Q - 4m_e c^2\]
\[Q - 2m_e c^2\]
Enhanced if V+A is at work

Resonant enhancement \((*10^6)\) of 0nu ECEC if excited state in daughter is degenerate (within 200 eV) with initial ground state \((- Q-values)\)

S. Zujkowskii, S. Wycech, PRC 70, 052501 (2004)
Resonant double EC

\[ \frac{1}{T_{1/2}} = C \times m_\nu^2 \times |M|^2 \times |\Psi_{1e}|^2 \times |\Psi_{2e}|^2 \times \frac{\Gamma}{(Q - B_{2h} - E_\gamma)^2 + \frac{1}{4} \Gamma^2} \]
Other issues/questions

- Ground state 0nu EC/EC? How could it happen?

2K captures forbidden because of 0±→0±, real photon forbidden,
-> KL-capture or virtual photon

3 options; internal conversion, e+e- pair production, 2K EC with 2 gammas

- Low energy precision tests of weak interactions

- ft-values of super-allowed transitions

\[ F_t \equiv f t(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) = \frac{K}{2G^2_Y(1 + \Delta^Y_R)} \]

- Q-values of mirror transitions (alternative CVC and V_{ud})

- Neutrino -electron angular correlation in beta decay

Other precision measurements with Penning traps???
More BSM stuff...

- Neutron - antineutron - oscillations

\[ \Delta B = -2, \Delta L = 0 \]
\[ \Delta B = -1, \Delta L = -1 \]
\[ \Delta B = 0, \Delta L = 2 \]

Proton decay

Double beta decay

Alternative to neutron beam is conversion within nucleus \( \rightarrow \) suppression factor

\[ T_A = (\tau_{n\bar{n}})^2 T_R \]

Suppression factors under debate ie nuclear models 30 years old\(, T_R \) seems to be higher for heavier nuclei

SNO: 1000 tons of D\(_2\)O! D lightest nuclei with neutron , Signal : Antineutron proton annihilation at rest

Can EFT help calculating suppression factor, branching ratios?

- Pauli Principle violation in nuclei... Experimental approach too simple???
Conclusion

• Double beta decay is of central importance for neutrino physics. Golden plated channel to probe fundamental character of neutrinos.

• Interesting times as both LHC and double beta probe TeV scale.

• Several next generation experiments started last (Candles, GERDA, KamLAND-Zen, EXO).
  First exciting results from Xe-experiments and GERDA next week.

• Further experiments are in the building up phase, several interesting experimental ideas are investigated.

• To go below 50 meV requires hundreds of kilograms of enriched material, lot of ideas...to cover uncertainties at least 3-4 isotopes should be measured.

• To support matrix element calculations as much experimental input as possible on nuclear structure is desired! We are only talking about 11 isotope pairs!!!
The future...

or

K. Zuber